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FIRST EVIDENCE FOR ELECTROWEAK RADIATIVE CORRECTIONS FROM THE NEW PRECISION DATA

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Abstract

The analysis of the newest data on the leptonic Z-decays and m_W appears to reveal the first manifestations of electroweak radiative corrections. In fact, these data differ, at the level of 2σ, from their electroweak Born values, while they agree, to within 1σ, with the theoretical values which take the electroweak radiative corrections into account. Previous data were within 1σ in agreement with both sets of values.

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The traditional way of analyzing the data on electroweak radiative corrections, (see for instance [1] - [3]), is to *not* split off from them the large and purely electromagnetic effect of the running of the electric charge from $q^2 = 0$ to $q^2 = m_Z^2$. According to that approach, which starts from $\alpha \equiv \alpha(0) = 1/137.0359895(61)$, the "electroweak" corrections appear to be large and to have been observed for a long time. By analyzing them, many authors [4] came already several years ago to the conclusion that the mass of the top quark must be close to 130 GeV or heavier.

In a series of papers [5]-[9] we developed an approach in which the running of $\alpha(q^2)$ is explicitly excluded from the genuinely electroweak corrections and included in the electromagnetic ones. Our main argument is that the running of $\alpha(q^2)$ up to $q^2 = m_Z^2$ is a purely electromagnetic phenomenon which is totally insensitive to the existence of electroweak bosons (W, Z and higgs), and that $\alpha(0)$, with all its impressive accuracy, is wholly irrelevant to electroweak physics even at low energy [10]. Our approach starts with the most accurately known electroweak observables:

$$G_\mu = 1.16639(2) \cdot 10^{-5} \quad \mathrm{GeV}^{-2} \ , \qquad [11] \qquad (1)$$

$$m_Z = 91.1899(44) \quad \mathrm{GeV} \ , \qquad [12] \qquad (2)$$

$$\bar{\alpha} \equiv \alpha(m_Z) = 1/128.87(12) \ , \qquad [13] \qquad (3)$$

and has three free parameters: the top quark mass, m_t, the Higgs boson mass, m_H, and the QCD coupling constant $\bar{\alpha}_s \equiv \alpha_s(m_Z)$. The conventional nature of the definition on $\bar{\alpha}$ is analyzed in [14].

In terms of G_μ, m_Z and $\bar{\alpha}$ we define the electroweak angle θ ($sin\theta \equiv s, cos\theta \equiv c$) [5], [6], [15]:

$$s^2c^2 = \frac{\pi\bar{\alpha}}{\sqrt{2}G_\mu m_Z^2}, \qquad (4)$$

which is analogous to, but different from, the traditional θ_W ($sin\theta_W \equiv s_W$, $cos\theta_W \equiv c_W$) defined by substituting α instead of $\bar{\alpha}$ in eq.(4). By solving eq.(4) one finds:

$$s^2 = 0.23118(33), \qquad c = 0.87682(19) \qquad (5)$$

In the $\bar{\alpha}$-Born approximation

$$m_W/m_Z = c = 0.8768(2), \qquad (6)$$

$$g_A = -1/2, \qquad (7)$$

$$g_V/g_A = 1 - 4s^2 = 0.0753(12). \qquad (8)$$

Here g_V and g_A are the vector and axial couplings of the Z boson decay into a pair of charged leptons $l\bar{l}$. (Note that with the traditional angle θ_W we would

get $s_W^2 = 0.2122$ and in the $\bar{\alpha}$-Born approximation $g_V/g_A = 0.1514$ which differs by 40σ (!) from the corresponding experimental value (see Table 1).

The width of the decay $Z \to l\bar{l}$ is given by expression:

$$\Gamma_l = 4(1 + \frac{3\bar{\alpha}}{4\pi})(g_A^2 + g_V^2)\Gamma_0, \tag{9}$$

where

$$\Gamma_0 = \frac{\sqrt{2}G_\mu m_Z^3}{48\pi} = 82.948(12) \quad \text{MeV} \tag{10}$$

The first bracket in eq. (9) takes into account the purely electromagnetic corrections.

In a similar manner, the width of Z decaying into a pair of quarks $q\bar{q}$ with charge Q and the isospin projection T_3 is given by

$$\Gamma_q = 12(1 + \frac{3Q^2\bar{\alpha}}{4\pi})(g_{Aq}^2 + g_{Vq}^2)\Gamma_0 G \tag{11}$$

where

$$g_{Aq} = T_3, \tag{12}$$

$$g_{Vq}/g_{Aq} = 1 - 4|Q|s^2. \tag{13}$$

The extra factor of 3, as compared with eq.(9), comes from the colour and the factor G takes into account the emission and exchange of gluons [16]:

$$G = 1 + \bar{\alpha}_s/\pi + 1.4(\bar{\alpha}_s/\pi)^2 - 13(\bar{\alpha}_s/\pi)^3 + ... \tag{14}$$

We thus define the $\bar{\alpha}$-Born approximation for Γ_l by eqs.(7)-(10) and for Γ_h by summing eq. (11) over all quarks, thereby taking into account the QED and QCD loop corrections. Beyond the $\bar{\alpha}$-Born approximation, one has to include in g_A, g_V, g_{Aq}, g_{Vq} the contributions of electroweak loops proportional to $\bar{\alpha}/\pi$ (with gluonic corrections in some of them).

In ref. [8] we concluded that the data of four LEP detectors, announced at the 1993 La Thuile [17] and Moriond [18] conferences, were, within 1σ, described by the electroweak $\bar{\alpha}$-Born approximation as well as by the standard model expressions including the one-loop electroweak corrections. This means that the genuine electroweak corrections were not visible experimentally at that time.

The non-observation of deviations from the electroweak $\bar{\alpha}$-Born approximation, with due allowance for QED and QCD effects, enabled us to predict the values of $\bar{\alpha}_s$ and m_t within the framework of the Minimal Standard Model, while m_H remained practically non-constrained. In this respect our results did not differ from those of the traditional approach. In our approach the possibility of constraining m_t arises from the mutual compensation of the

contributions of the top quark and all other virtual particles for m_t in the range of 160 ± 20 GeV [8].

The experimental data changed somewhat by the time of the Marseille Conference [19],[3], so that the maximal deviation from the corresponding $\bar{\alpha}$-Born value became 1.3σ (for g_V/g_A) [9]. Obviously, the situation did not change qualitatively.

According to the fit of ref. [9], the values of the LEP observables were equally well described within 1σ by the $\bar{\alpha}$-Born approximation and by the Minimal Standard Model amplitudes including the electroweak radiative corrections. The only exception was the value of R_b for a heavy higgs where discrepancy with the MSM prediction reached 1.7σ. (See Table 1 from [9].)

At the 1994 La Thuile and Moriond conferences [12] new, more accurate data were presented by CDF, ADLO and SLD. In the present note we compare these data with our theoretical expressions, which have been combined into a computer code called LEPTOP [1].

Let us start by considering the data of CDF and ADLO. From Table 1 we see that the new experimental values of m_W/m_Z, Γ_l and g_V/g_A deviate from their $\bar{\alpha}$-Born value by 2σ. These are the so-called "gluon-free" observables [20] which depend on $\bar{\alpha}_s$ only very weakly, i.e., only through terms of the order of $\bar{\alpha}\bar{\alpha}_s$. At the same time the data agree within 1σ with those theoretical predictions which take the electroweak radiative corrections into account. *We consider this as a first indication that the genuine electroweak corrections have become observable.* This conclusion is strengthened by the fact that the experimental errors in m_W/m_Z, Γ_l and g_V/g_A are practically uncorrelated. Note the difference between our statement and that of Ref. [21] where the departure of the MSM predicted (fitted) values from the $\bar{\alpha}$-Born ones is being stressed.

There are two small clouds on this blue sky. First, the new measurements of A_{LR} at SLD give $sin^2\theta_{eff} = 0.2290(10)$ or $g_V/g_A = 0.0840(40)$, which differs by 3σ from the LEP value $g_V/g_A = 0.0711(20)$ and from the theoretical prediction (see Table 1). This discrepancy is probably of purely experimental origin. Note that the SLD value for g_V/g_A lies 2σ above the $\bar{\alpha}$-Born value, while the LEP value lies 2σ below. Their average is compatible with $\bar{\alpha}$-Born.

Second, the value of R_b measured at LEP coincides with the $\bar{\alpha}$-Born value and is 2.5σ away from its theoretically fitted value $R_b = 0.2161(4)^{-6}_{+6}$ with the central value corresponding to $m_H = 300$ GeV, the shifts + (−) 6 to $m_H = 60(1000)$ GeV, and the uncertainty ± 4 to $\delta m_t = \pm 11$ GeV. This discrepancy may, if not caused by a systematic error, indicate the existence of new physics [19].

Let us note that the figures presented in the Table correspond to the

[1] One can obtain the FORTRAN code of LEPTOP from rozanov@cernvm.cern.ch

fitted values of m_t and $\bar{\alpha}_s$ derived from the new LEP and CDF data:

$$m_t = 171(11)^{+15}_{-21}(5), \tag{15}$$

$$\bar{\alpha}_s \equiv \alpha_s(m_Z) = 0.125 \pm 0.005 \pm 0.002, \tag{16}$$

$$\chi^2 = 14/10. \tag{17}$$

Here the central values correspond again to $m_H = 300$ GeV, with the first uncertainties being experimental, the second corresponding to $m_H = 300^{+700}_{-240}$ GeV, and the third (for m_t) corresponding to the uncertainty in $1/\bar{\alpha} = 128.87 \pm 0.12$.

Comparing this with the fit [9] of the earlier data:

$$m_t = 162^{+14+16}_{-15-22}, \tag{18}$$

$$\bar{\alpha}_s = 0.119 \pm 0.006^{+0.002}_{-0.003}, \tag{19}$$

$$\chi^2 = 3.5/10, \tag{20}$$

we observe that central values of m_t and α_s have increased, their uncertainties decreased, while the χ^2 became more palatable. The individual contributions to the average value of m_t show more variations than previously (see Fig. 1).

Our new fitted values for m_t and $\bar{\alpha}_s$ are in good agreement with these of the LEP Electroweak Working Group as obtained in the traditional approach and presented at the Moriond Conference [12].

The numbers of the fit (15)–(17) and of Table 1 include a recently estimated QCD correction [22], which increases m_t by about 4 GeV.

With reference to Table 1, we would like to stress two points:

(1) The shifts caused by changing m_H are, as a rule, small compared to the uncertainties (in brackets) in column 5. This "m_H independence" is characteristic for the global fit which predicts m_t for a given m_H. The higher m_H, the higher is the predicted m_t, while the predicted values of the observables remain practically unchanged. (This would be evident if there was only a single observable).

(2) The situation is different when m_t is fixed (e.g., measured). For $m_t = 170$ GeV, the shifts of g_V/g_A from its central value 0.0711 are –0.0024 and +0.0035 for $m_H = 1000$ GeV and 60 GeV, respectively (see Table 2 of Ref. [6]), which is larger than the current experimental uncertainty in $g_V/g_A(\pm\, 0.0020)$. Thus a further improvement of the accuracy in g_V/g_A could place serious bounds on m_H. Two other "gluon-free" observables, m_W/m_Z and g_A, are less sensitive: their higgs shifts are half as large as their present experimental uncertainties.

To conclude: Within the framework of the traditional approach, which starts with $\alpha(0)$, the latest precision data do not herald anything qualitatively new; one merely gets a slightly heavier top mass, and a slightly larger strong coupling constant. In strong contrast, these same data open, with our approach – which starts with $\alpha(m_Z)$ – a new window, one through which the non-vanishing electroweak radiative corrections become visible.

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Table 1

Results of fitting the Moriond 1994 data from LEP and $p\bar{p}$ colliders. Observables (first column), their '94 and '93 experimental values (second and third columns) and their predicted values: (a) in the electroweak tree (Born) approximation based on $\bar{\alpha}$ (fourth column) and (b) in the electroweak tree plus one loop approximation (fifth column). Both in columns 4 and 5 the QED and QCD loops were taken into account.

The predicted values have been obtained for three fixed values of $m_H = 300^{+700}_{-240}$ GeV; for each of them the fitted values of $m_t \pm \delta m_t$ and $\bar{\alpha}_s \pm \delta\alpha_s$ were used. The central values correspond to $m_H = 300$ GeV. The upper (lower) numbers give the shifts of these central values corresponding to $m_H = 1000$ (60) GeV.

The numbers in brackets correspond to experimental uncertainties (columns 2 and 3), and predicted uncertainties (columns 4 and 5), arising in column 4 from $\delta\bar{\alpha}$ for m_W/m_Z, g_V/g_A and Γ_l and from $\delta\bar{\alpha}_s$ for the five other observables. The errors in brackets in column 5 come from $\delta\bar{\alpha}_s$ and δm_t of the fit and from $\delta\bar{\alpha}$ (for g_V/g_A only). Note that the $\bar{\alpha}$-Born values of hadronic observables depend on m_H. This is caused by their dependence on $\bar{\alpha}_s$, the fitted values of which depend on m_H.

Observable	Exp. '94	Exp. '93	$\bar{\alpha}$-Born	MSM prediction
m_W/m_Z	0.8814(21)	0.8798(28)	0.8768(2)	$0.8803(8)^{+0}_{-2}$
g_V/g_A	0.0711(20)	0.0716(28)	0.0753(12)	$0.0711(19)^{-7}_{+9}$
Γ_l (MeV)	83.98(18)	83.82(27)	83.57(2)	$83.87(11)^{+0}_{-6}$
Γ_h (GeV)	1.7460(40)	1.7403(59)	$1.7445(26)^{+11}_{-9}$	$1.7435(27)^{-3}_{-5}$
Γ_Z (GeV)	2.4971(38)	2.4890(70)	$2.4930(26)^{+10}_{-10}$	$2.4962(32)^{-3}_{-12}$
σ_{had} (nb)	41.51(12)	41.56(14)	$41.41(3)^{-10}_{+9}$	$41.43(3)^{+0.2}_{-0.6}$
R_l	20.790(40)	20.763(49)	$20.874(31)^{+13}_{-11}$	$20.788(32)^{-5}_{+10}$
R_b	0.2210(19)	0.2200(27)	$0.2197(0)^{+0}_{-0}$	$0.2161(4)^{-6}_{+6}$

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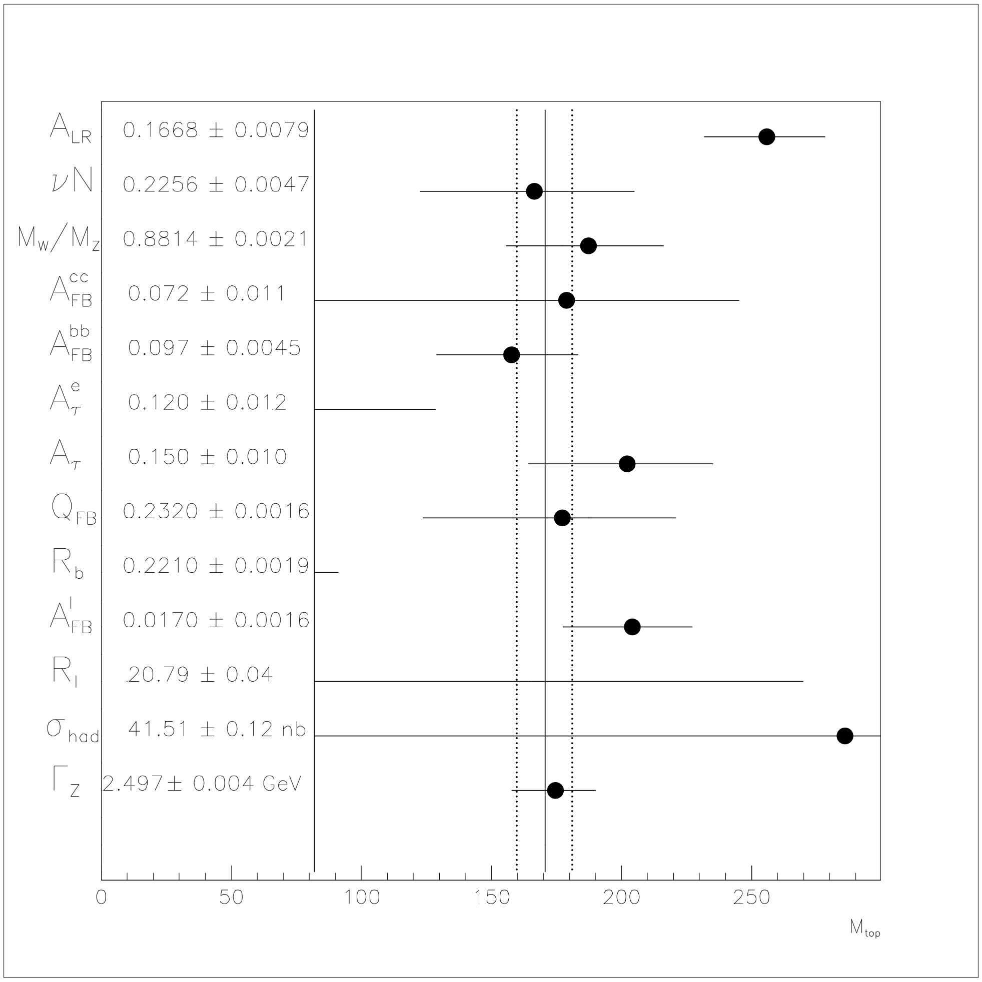
Figure Captions

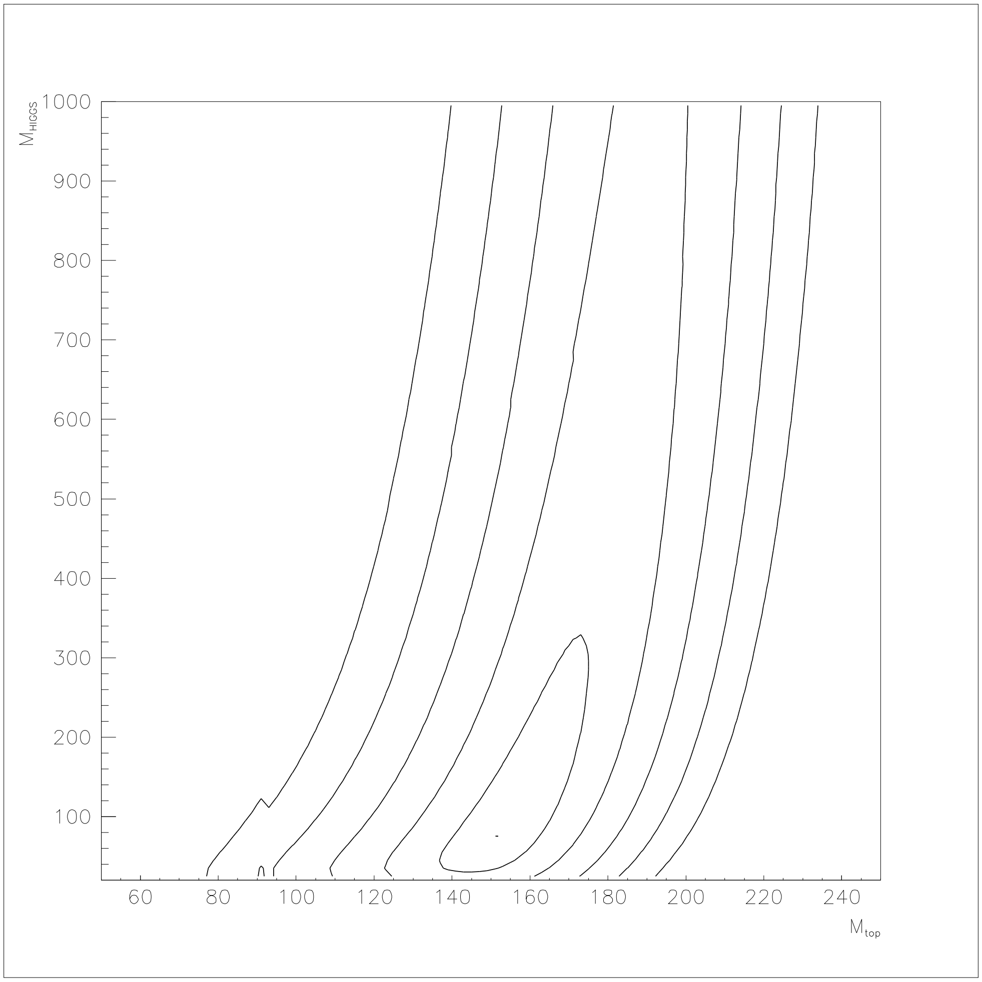
Fig. 1: The fitted values of m_t from the specified observables measured at LEP and $p\bar{p}$ colliders, assuming $m_H = 300$ GeV and $\bar{\alpha}_s = 0.125$. The region $m_t < m_Z$, is definitely excluded by the direct searches. The central values of m_t from R_b, A^e_τ and R_l lie in this excluded region.

Fig. 2: Allowed region of m_t and m_H with $\bar{\alpha}_s = 0.125$. The lines represent the s-standard "ellipses" (s=1,2,3,4,5) corresponding to the constant values of χ^2 ($\chi^2 = \chi^2_{min} + s^2$).



A_{LR} 0.1668 ± 0.0079
νN 0.2256 ± 0.0047
M_W/M_Z 0.8814 ± 0.0021
A_{FB}^{cc} 0.072 ± 0.011
A_{FB}^{bb} 0.097 ± 0.0045
A_{τ}^{e} 0.120 ± 0.012
A_{τ} 0.150 ± 0.010
Q_{FB} 0.2320 ± 0.0016
R_b 0.2210 ± 0.0019
A_{FB}^{l} 0.0170 ± 0.0016
R_l 20.79 ± 0.04
σ_{had} 41.51 ± 0.12 nb
Γ_Z 2.497± 0.004 GeV
0
50
100
150
200
250
M_{top}

Figure 1:



M_{HIGGS}
1000
900
800
700
600
500
400
300
200
100
60
80
100
120
140
160
180
200
220
240
M_{top}

Figure 2: